The Change of the Electric Resistance of Bismuth Crystals in Strong Magnetic Fields : Part II. Experimental Results. The Change of Resistance of Bismuth Crystals in a Magnetic Field with the Current perpendicular to the Field

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The Change of the Electric Resistance of Bismuth Crystals in Strong Magnetic Fields.

Part II. Experimental Results.

The Change of Resistance of Bismuth Crystals in a Magnetic Field with the Current perpendicular to the Field

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I. Introduction

The study of the change of resistance of bismuth crystals in a magnetic field is an involved problem in which a number of variables must be account.

In the first place, the change of resistance of bismuth crystals depends on the strength of the field; secondly, on the direction of the current relative to the axis of the crystal; thirdly, on the orientation of the crystal in the field, and finally on the temperature.

It also depends on the chemical purity of the bismuth, on the state of perfection of the crystal lattice and on the strains which may be set up in the crystal.

Kapitza has been made the experiments on the change of resistance of bismuth crystals in magnetic fields up to 300 kilo-oersted with the current perpendicular to the field at 290°, 193° and 91° absolute.[1].

It has been shown that in weak fields the change of resistance follows the square of the field and in stronger fields it is proportional to the field. In weak fields the change of resistance is practically independent of the orientation of the crystal in the field. It has also been shown that the impurities and imperfection in the crystal lattice greatly influence to the change of resistance at low temperature and in strong fields.

In this paper, it is proposed to give a detailed description on the change of resistance of bismuth crystal in a magnetic fields up to 200 kilo-oersted with the current perpendicular to the field at room temperature. The current is sent through the crystal for different orientations of the axis of the crystal relative to the field.

II. Single Crystal

Bismuth crystallises in the trigonal system and its crystallising system is that of ditrigonal scalenohedron, represented by the space group D^5_{3d} in which two face-cen-

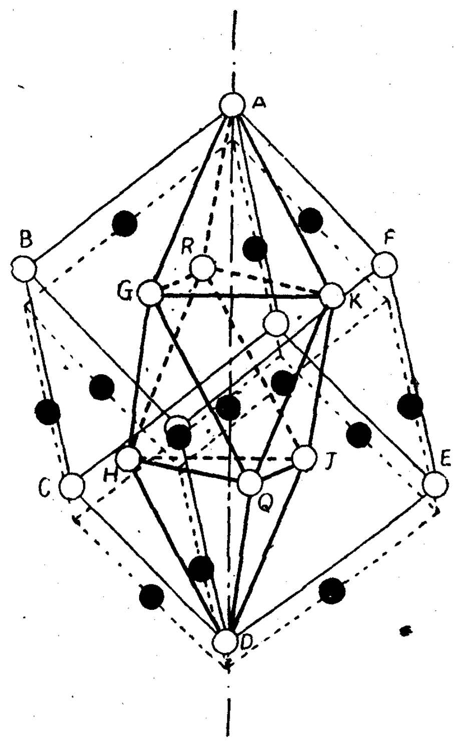

Fig. 1.

tered rhombohedral lattice intespenetrate to each other to set the second lattice points in anoccupied spaces of the first lattice points (Fig. 1). On the other hand this crystal structure may be considered as the system of three equilateral trigonal prisms interpenerate to each other to occupy the lattice points AGHDJKA given on Fig. 1.

In bismuth crystal, there are four cleavage planes which from the pseudo-octahedral plane RGHQJKR (Fig. 1) and one of them, namely (111), is the perfect cleavage plane perpendicular to the trigonal axis. The perfect cleavage plane has three sets of lines of equal strength intersecting at 60°, runing parallel to the intersection of the three imperfect cleavage planes of the pseudo-octahedron. These lines run also parallel to the three binary axis. Each imperfect cleavage planes GHQ, KQJ, RHJ, respectively, has three sets of lines also, in which one set runs parallel to the perfect cleavage plane intersecting the remaining sets of lines at 61° 22′ and the other two sets run parallel to the remaining imperfact cleavage planes intersecting in each other at 57° 16′.

From the trigonal pyramid AGKR, it is clear that three imperfect cleavage planes intersect at *A* inclining to the perfect cleavage planes at 71° 38′. Therefore, the typical specimens, in the form of rods, are selected as follow:

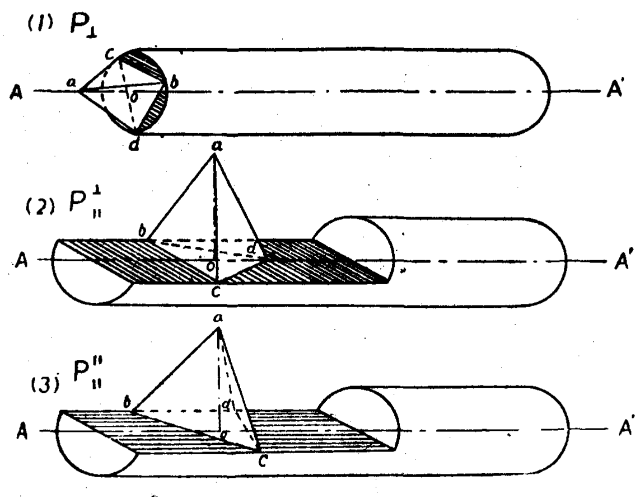

Fig. 2.

(1) The axis of the rod is perpendicular to the perfect cleavage plane, i.e., parallel to the trigonal axis (Fig. 2, (1)). $\mathbf{P}_\perp$.

(2) The axis of the rod is parallel to the perfect cleavage plane.

(a) The axis of the rod is perpendicular to one of the binary axis in the plane (Fig. 2. (2)), $\mathbf{P}_{\parallel}^{\perp}$.

(b) The axis of the rod is parallel to one of the binary axis in the plane (Fig. 2, (3)). $\mathbf{P}_{\parallel}^{\parallel}$.

In the case of (2a), one of the binary axis is perpendicular to AA′ and the remaining two run oblique to AA′ intersecting at 30° but in the case of (2b), it is parallel to AA′ and the remaining two run oblique to AA′ intersecting at 60°.

Following several ways of attack were tried before a satisfactory crystal was obtained. At first, bismuth rods with a neary equal diameter of 1 mm and 100 to 200 mm in length were made, using chemically pure bismuth (Bi 99.986%. Cu 0.002%, Fe 0.006% S 0.006%), by drawing up from molten bismuth into small glass tubes and then dissolving glass tubes in hydrofluoric acid. Finally, these bismuth rods were crystallised.

(1) A copper plate method in vacuum tube: a method is simillar to that used by Kapitza.

(2) In the cylindrical furnace with an inner diameter 20 mm, 60 cm in length which had the temperature gradient along the axis of the furnace, a glass tube with an inner diameter 5 mm, 100 mm in length was fixed parallel, glancing slightly aside to the centre of the furnace. The bismuth rod fixed in this glass tube was grown to crystal by moving the furnace very slowly with crockwork in hydrogen atmosphere.

(3) A method of growing crystals by remelting in hydrogen atmosphere, placing the bismuth rod in the cylindrical furnace with the uniform temperature distribution.

The detailed description of the characteristic properties of the crystal obtained are given in a separate paper.

The crystallographic orientation of many crystal rods can easily been determined by the method of etching figure.

The perfect cleavage plane can easily been cleaved and the direction of the binary axis on this plane are determined by the microscopic observation. As the crystal rod in which the axis of the rod is parallel to this plane is generally very flexible, it was tried to cleave this plane carefully in the liquid air vessel with a pincette by very weak force, giving no strain in the crystal.

The inclination of the perfect cleavage plane to the axis of the rod can roughly inferred from the anisotropy of the physical properties. For instance, the relation between this angle and the value of the specific resistance at room temperature is illustrated on Table 1 and Fig. 3, corresponding $\theta°$ to the axis of the rod parallel to the cleavage plane and 90° to the axis of the rod perpendicular to this plane. It is clear that the Voigt-Thomson's law, i.e., $\cos^2$-law, was fairly satisfied. The measuring points were distributed mainly in the range of 0° to 30° and rare in the more great angle showing that it is difficult to obtain the crystal rods with an angle of 45° and 90° as in the case of Zn crystal rods. Further, the value of the specific resistance become greater when stressed, even so the angle is the same. Therefore, it must be carefully selected the crystal.

Table 1.

Angle between the axis of the rod and the trigonal axis (Degree)	Specific resistance (ohm cm) (13°～18° C)
0	107.42 $\times 10^{-6}$
0	108.35
0	108.76
0	108.82
5	109.08
7	109.29
8	110.26
9	109.58
11	110.01
12	109.44
12	110.57
13	111.19
15	111.04
17	112.42
19	112.40
20	113.14
23	114.76
31	118.34
32	118.84
33	120.39
36	121.63
41	123.44
46	126.00
48	126.63
50	126.57
50	126.80
52	128.09
57	130.35
59	131.77
78	137.40
85	138.20
90	137.94

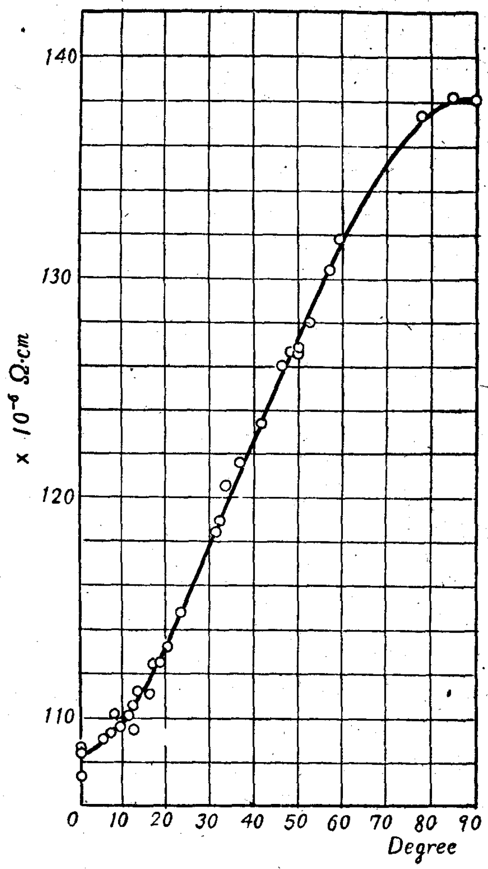

Fig. 3.

III. Crystal $P_\perp$

A crystal rod, 6.7 mm long and 1.01 mm in diameter is used which initial resistance is 0.01155 ohm at 12°C.

As the axis of the crystal is parallel to the trigonal axis, the current is flowing along the trigonal axis and the field is parallel to the perfect eleavage plane.

The method employed for measuring the change of resistance were described in Part I. Fig. 4 contains the results of the observation for effect of the orientation of crystal when it is rotated around the trigonal axis in the following cases:

(1) The field is perpendicular to one of the binary axis in the perfect cleavage plane.

(2) The field makes an angle of 15° to the binary axis.

(3) The field is parallel to the binary axis.

The example of an oscillogram in the case of (1) is given on Photo. I. It may be remarked that all the curves in Fig. 4 are of a similar character. At the beginning

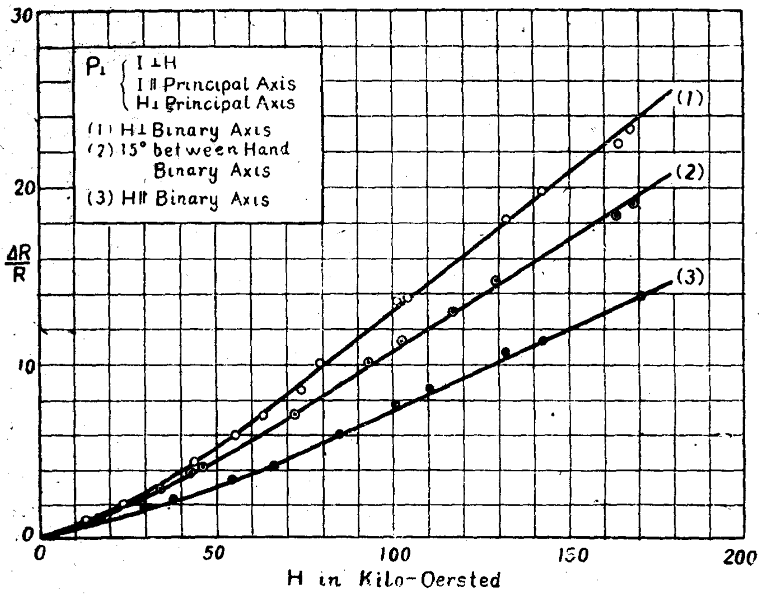

Fig. 4.

within somewhere 30 kilo-oersted, the resistance changes as the square of the field and at stronger field up to 180 kilo-oersted the change is proportional to the field. When the crystal is rotated around the trigonal axis, six similar orientations of the crystal relation to direction of the field is possible. In the first set, given by the curve (1), the maximum change of resistance in a magnetic field is obtained. When the crystal is turned through 30°, the increase of resistance becomes to minimum as given by the curve (3). When the crystal is turned through 45°, the increase of resistance becomes to middle value of above two sets as given by the curve (2). In turning the crystal around its axis in a strong field where the change is proportional to the field, these minima and maxima repeat themselves with a periodicity of 60°, and the variation in the change of resistance at a constant field almost approches to a sine curve. This phenomenon was studied by Kaye[2] and Stierstadt[3] in weak fields at room temperature. From the present experiments it may be concluded that their results can be held at least in strong fields up to 180 kilo-oersted.

In measuring the change of resistance of bismuth crystals, it is neccessary to eliminate the time lag phenomenon as already mentioned by Kapitza and the magnitude of the lag phenomenon is most marked for a crystal where the current is passing perpendicular to the cleavage plane, and where the current is also perpendicular to the lines of force of the field. For clearness, two curves taken from oscillograms (Photos. 1, 2) are shown in Fig. 5 in which I-and R-curves are drawn to lie together corresponding (1) to $\mathbf{P}_\perp$ crystal and (2) to $\mathbf{P}_{\parallel}^{\parallel}$ crystal. In the case (1), the resistances at A and B in I-curve which correspond to the same field, are CC′ in ascending and AA′ in descending of the fields. This curve shows clearly CC′>AA′ and moreover the resistance decreasing as it approches to the end point of the horizontal part of I-curve. In the case of (2), the resistances at A and B in I-curve which correspond

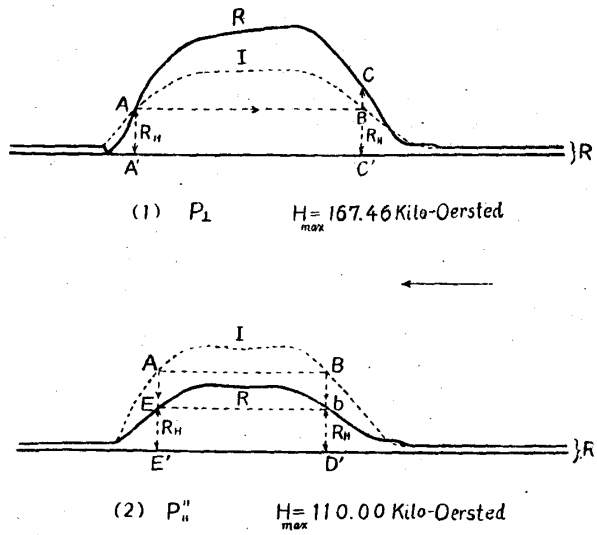

Fig. 5.

to the same fields are DD′ in ascending and EE′ in descending of the fields. This curve shows clearly DD′=EE′ in the experimental error, and moreover the resistance preserving the same value in the horizontal part of I-curve, indicating that the time lag phenomenon could scarecely be observed. This phenonmena is most markedly in $\mathbf{P}_\perp$ crystal. In other crystal, it is as same order as in the case of $\mathbf{P}_{\parallel}^{\parallel}$ crystal. Therefore, in observing the change of resistance to concern ourselves particularly about the time lag phenomenon, measuring points were adopted only the points in the ascending part and the beginning of the horizontal part of I-curve. So that, the measuring points of $\mathbf{P}_\perp$ crystal may have some error as they compared with those of the other crystals.

IV. Crystal $P_{\parallel}^{\perp}$

A crystal rod, 6.5 mm long and 0.95 mm in diameter is used which initial resistance is 0.00983 ohm at 20°C.

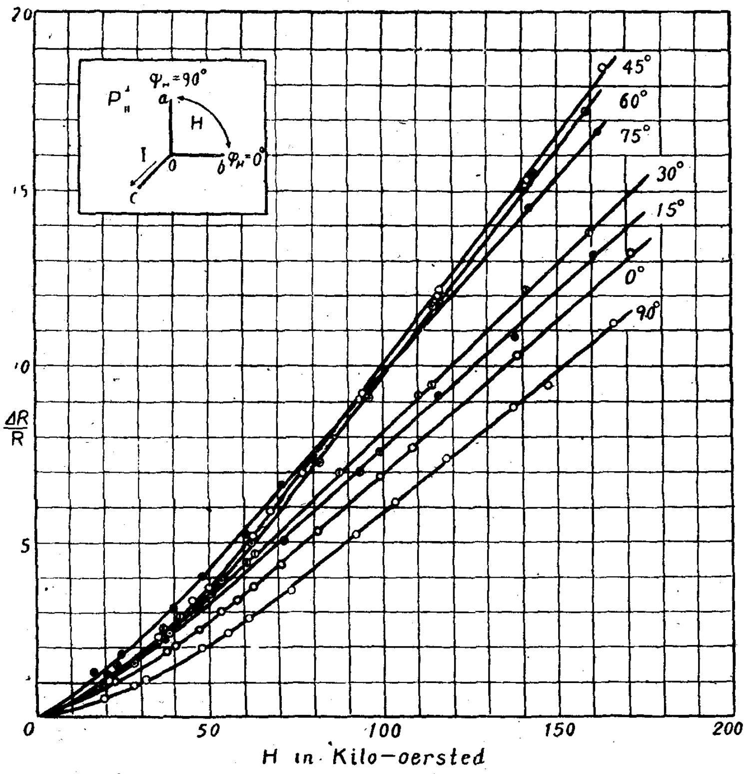

Fig. 6.

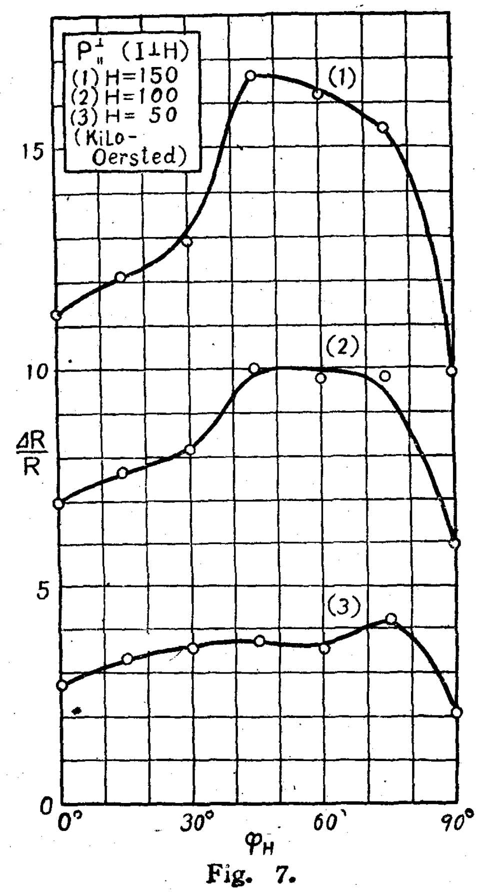

Fig. 7.

As the axis of the crystal is not entirely perpendicular to one of the binary axis, making an angle of 3°, the current is flowing perpendicular to the trigonal axis and along the direction of an angle of 87° to one of the binary axis. Figs. 6, 7 contain the results of the observation for the effect of the orientation of the crystal when it is rotated around the axis of the rod. From the relation among the crystal structure, the field and the current, in Fig. 8, the current is always flowing nearly along R o c, and the direction of a field is rotated from o b ($\varphi_H=0°$) to o a ($\varphi_H=90°$) in the o a′ b a plane, containing the trigonal axis inclined (to the AGQKplane) at 18°22′. The effects occured in the other three quadrants are symmetrical refer to R o c. As the observations are performed at each 15°, the error of the measurment of the angle of rotation amounts nearly ±5° since the setting of the small specimen can not perfectly performed. From Fig. 6, it may be remarked that the resistance changes proportional to the square of the field or to the field, at the beginning within 30—50 kilo-oersted or at stronger fields, respectively. When the field is parallel to the trigonal axis ($\varphi_H=90°$), the minimum increase of the resistance is obtained. When φ_H is increased from 0°, the change becomes greater with approching to 30°, and then, follows sudden

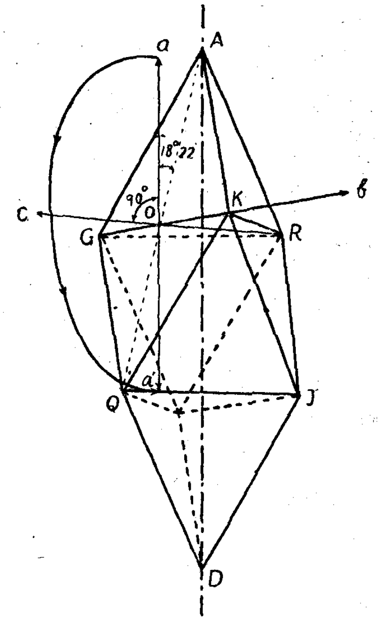

Fig. 8.

decreasing nearly at 70°. These sudden changes are noticeable in strong fields, (1), (2) in Fig. 7, and in the case of (1), the maximum change is occured near 45°.

V. Crystal $P^{\parallel}_{\parallel}$

A crystal rod, 6.2 mm long and 0.86 mm in diameter is used which initial resistance is 0.0116 ohm at 12°C.

The current is flowing along one of the binary axis, i. e., perpendicular to the trigonal axis. The effect of the orientation of the crystal is observed when it is rotated around the axis of the rod: that is, in Fig. 8, the current is flowing along GK, and a magnetic field is applied to the direction perpendicular to the current in the a c a′ o plane, from o a ($\varphi_H=0°$) to o a′ ($\varphi_H=180°$) at each 15°. In this case, a c a′ o plane is perpendicular to the imperfect cleavage plane AGQK and hence the change of resistance is repeated with a periodicity of 180°. The results are given on Figs. 9, 10. From Fig. 9, it is cleared that the change of resistance is followed to the square of the field up to 30-50 kilo-oersted and then it is proportional to the field at strong fields From Fig. 10, the maximum and the minimum changes of resistance are occured in the neighbour of 70° and 150°, respectively. The directions of the field corresponding to these cases are equivalent to the orientations perpendicular and parallel to the imperfect cleavage plane AGQK (Fig. 8), respectively. As AGQK plane is inclined to the trigonal axis at 18° 22′, the positions of the fields perpendicular and parallel to this plane correspond to $\varphi_H=$ 71° 38′ and 161° 38′, respectively. The discrepancy of the extremum positions in the experiments may be ascribed to the allowable experimental error. Therefore, it is reasonable to suppose that the relation already studied by Stierstadt with an electromagnet, the change of resistance repeated with a periodicity of 180°, can be also held in strong field up to 180 kilo-oersted, but the displacement of the position of the maximum change of resistance with the intensity of a magnetic field as stated by Stierstadt can not find at strong fields in which the change of resistance is proportional to the field.

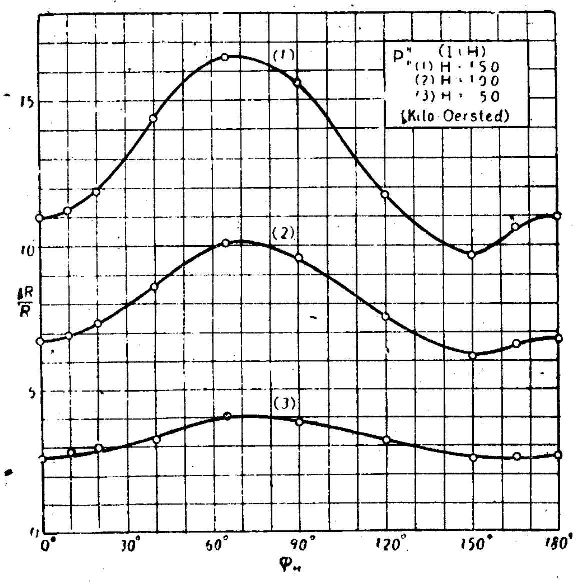

Fig. 10.

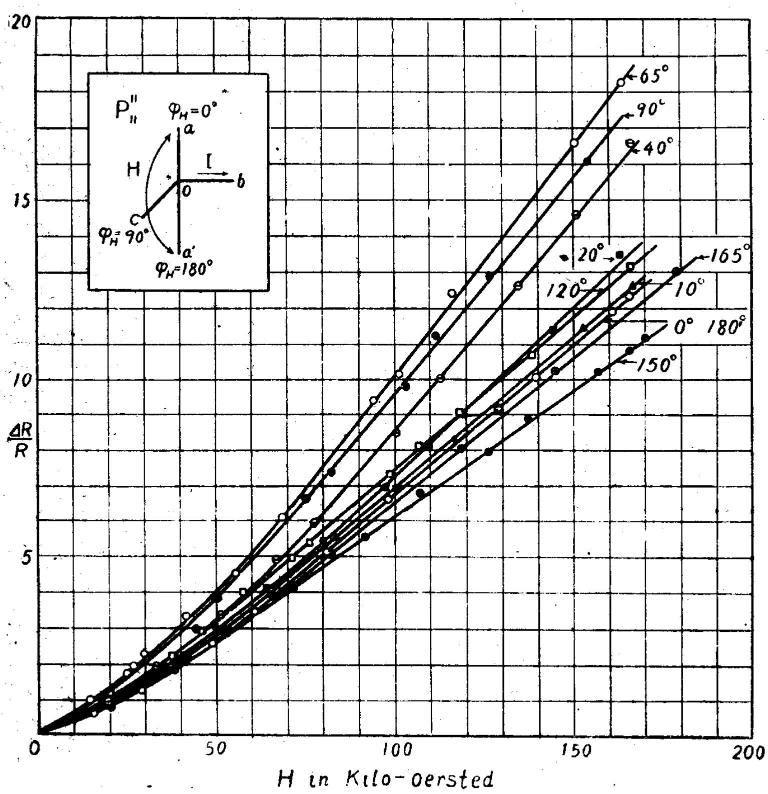

Fig. 9.

For the comparison with the experimental data of $P^{\parallel}_{\parallel}$, a crystal rod, 6.7 mm long and 0.83 mm in diameter is used which initial specific resistance is 114.76×10⁻⁶ ohm cm at 17°C. The perfect cleavage plane of this crystal inclined to the axis of the rod at 23°, and one of the binary axis inclined to the axis of the rod at 7°. (Notation $\mathbf{P}^{7}_{23}$).

The results taking from two main cases are given on Fig. 11, first where the field is parallel to the perfect cleavage plane, and the current is parallel to the axis of the rod, (Fig. 11 (1)) and the second where the field is turned around the axis of the rod by 90° from the first position (Fig. 11 (2)). The diagram of Fig. 11 shows that the change of resistance in (1) is greater than (2) as in the case of $\mathbf{P}^{\parallel}_{\parallel}$ and the change of (1) in $\mathbf{P}^{7}_{23}$ is smaller than $\mathbf{P}^{\parallel}_{\parallel}$, probably because of the inclination of the binary axis and the change of (2) in $\mathbf{P}^{7}_{23}$ is almost same as in $\mathbf{P}^{\parallel}_{\parallel}$.

The comparison of the change of resistance among six main cases adopted from $\mathbf{P}_{\perp}$, $\mathbf{P}^{\top}_{\parallel}$, $\mathbf{P}^{\parallel}_{\parallel}$, is given on Fig. 12. It is easily seen that the change of resistance is the greatest when the current is parallel to the trigonal axis and the field is parallel to oc and is small when the field is parallel to the trigonal axis. In strong field where the change is proportional to the field, the effect of the orientation of the crystal depends mainly on the relative position among the field, the perfect and the imperfect cleavage plane.

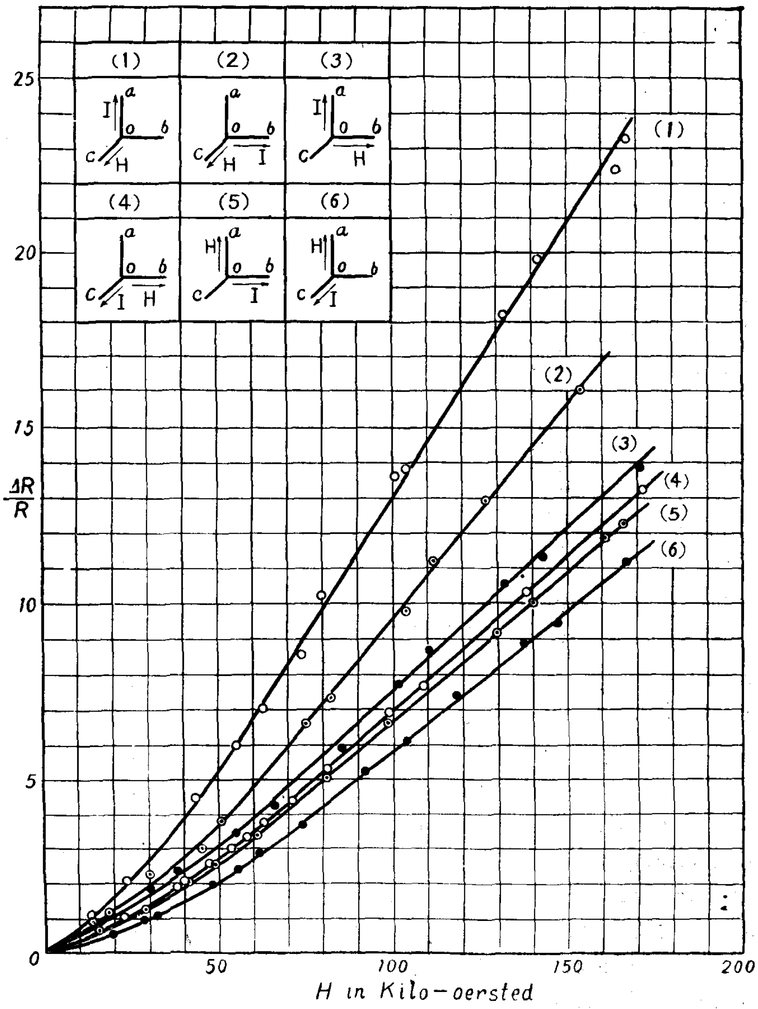

Fig. 12.

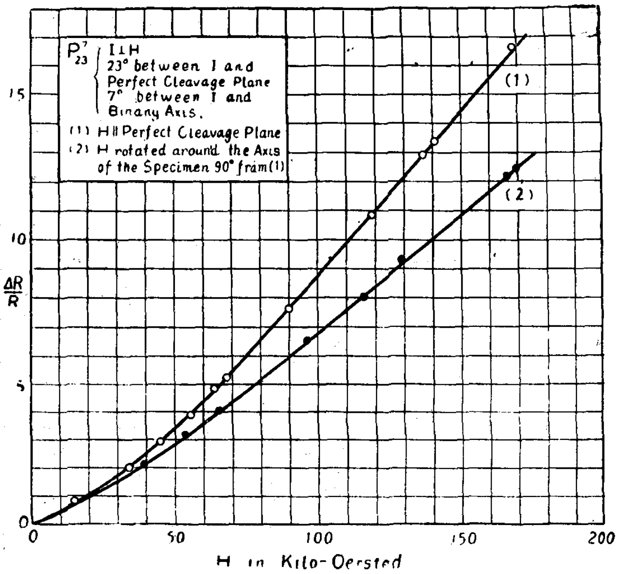

Fig. 11.

VI. Bismuth Polycrystal

Two polycrystals were used, prepared from the same bismuth as single crystals, No. 1, which was 6.8 mm long and 0.67 mm in diameter, and an initial specific resistance of 137.8×10^{-6} ohm cm at 15°C and, No. 2, which was 6.2 mm long and 1.5 mm in diameter, and an initial specific resistance of 112.7×10^{-6} ohm cm at 15°C. The change of resistance is given on Fig. 13. It is easily seen that at the beginning within somewhere 40 kilo-oersted, all the curves follow the square of the field and the changes are practically the same magnitude but at stronger fields, the change of No. 1 is slightly greater than that of No. 2. When the changes of polycrystals are compared with those of single crystals, there is a great similarity in the change of resistance but the magnitudes of polycrystals lie in practically the mean value of single crystals shown on Fig. 12: that is, the change of No. 1 is slightly larger than (3)

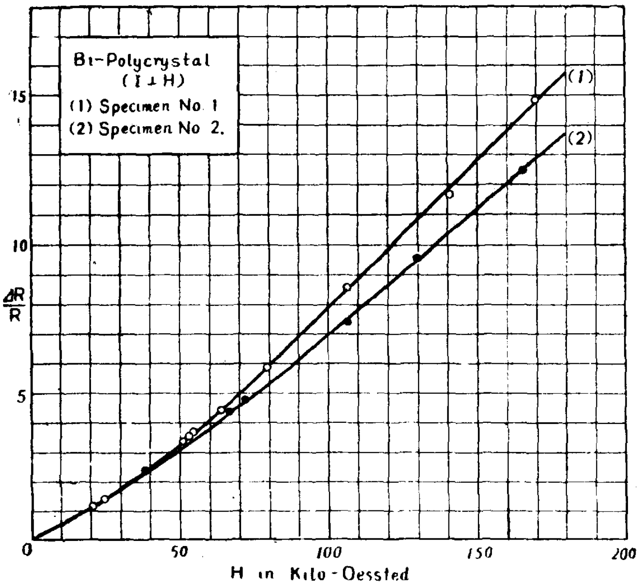

Fig. 13.

and the change of No. 2 is as same magnitude as (4) and (5).

As the grain sizes of these two polycrystals are nearly equal dimensions, the differences of the initial specific resistance and the change of resistance are ascribable to the effect of the orientation between the axis of the rod and the trigonal axis of each crystalline grains. This effect is not obvious in the weak field as seen from Fig. 13 but at stronger fields, it has been very marked.

Summary

Experimental results are given for the change of resistance of bismuth crystals and polycrystals when the current is perpendicular to the field for different orientations of the axis of bismuth crystal relative to the field.

The measurements have been made at room temperature and in a strong magnetic field up to 200 kilo-oersted.

It has been shown that in weak fields up to 30-50 kilo-oersted the change of resistance follows the square of the field, and in strong fields it is proportional to the field.

The change of resistance is dependent of the orientation of the crystal relative to the field.

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References

(1) P. Kapitza: Proc. Roy. Soc. London., A 119 (1928), 401.
(2) G. W. C. Kaye: Proc. Roy. Soc. London., A 170 (1939), 591.
(3) O. Stierstadt: Zeits. f. Physik., 85 (1933), 310.

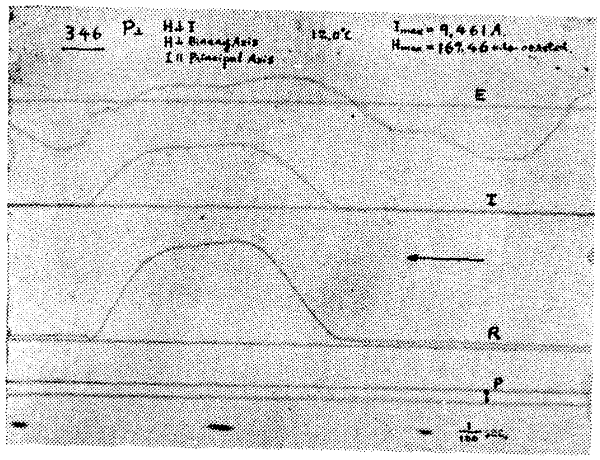

Photo. 1.

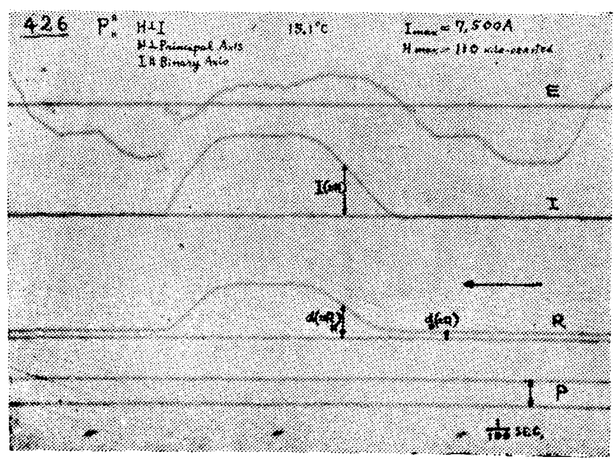

Photo. 2.